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Turbulent flow of viscoelastic shear-thinning liquids through a rectangular duct: Quantification of turbulence anisotropy

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ABSTRACT

We report laser Doppler anemometry (LDA) measurements of mean velocity and turbulence structure for fully-developed turbulent flow through a rectangular duct of aqueous solutions of a xanthan gum and a polyacrylamide both of which are drag-reducing polymer solutions. All three components of the turbulent fluctuations (i.e. the Reynolds normal stresses) have been measured as well as the Reynolds shear stress $-\rho\overline{uv}$. A novel open-slit test-section allows measurement of the component of Reynolds normal stress perpendicular to the duct wall and of the Reynolds shear stress down to values of y^+, the distance from the surface in wall units, close to unity. We show that the maximum value of the transverse (or normal) component of turbulence intensity in wall units v'^{+}_{MAX} decreases linearly from about unity for zero drag reduction (DR_1) to about 0.6 at $DR_1 = 80\%$ while the lateral component w^{+}_{MAX} is practically independent of DR_1. For levels of drag reduction below 50% the streamwise component u'^{+}_{MAX} increases monotonically but for higher levels of drag reduction the trend is less clear. Anisotropy of the turbulence structure is characterised using Pope's modification [S. Pope, Turbulent flows (2000), Cambridge University Press, New York.] of the triangle plot suggested by Lumley [J.L. Lumley, Computational modelling of turbulent flows, Adv. Appl. Mech. 18 (1978) 123–176] and shown to follow closely the line for axisymmetric turbulence. The detailed LDA measurements are supplemented by particle-image velocimetry observations which reveal how drag reduction changes the near-wall streaky structure.

1. Introduction

It has been known for 60 years [1] that large reductions in turbulent frictional drag occur when high molecular-weight polymers, surfactants, etc. are added to a Newtonian solvent even at very low concentrations (as little as a few ppm). Recent advances in numerical modelling, especially Direct Numerical Simulations (e.g. [2–6]) have enhanced our understanding of how the additives interact with and modify the turbulence and reduce the frictional drag. At the same time, efforts are being made to develop modelling approaches to such flows which are far less demanding of computational resources and so suitable for routine engineering calculations in complex geometries (e.g. [7–9]). The purpose of the work presented here is to provide a more comprehensive experimental database than has been available hitherto to assist in the development and validation of both approaches, particularly for higher polymer concentrations where there are measurable differences in shear viscosity and other fluid properties when compared with the solvent and for which currently there are no data. Special emphasis here will be placed on the quantification of turbulence anisotropy which many previous studies have shown qualitatively is significantly different for drag-reducing liquid flows compared to the turbulent flow of a Newtonian fluid.

Previous experimental work, outlined in Table 1, on the turbulent flow of non-Newtonian liquids through a rectangular duct [10–24] is limited in several ways. Several of these studies [10–15] have been concerned with flow through square ducts where the low aspect ratio leads to a three-dimensional rather than a two-dimensional flow field and there may also be secondary-flow effects [14], particularly at low polymer concentrations for modestly drag-reducing additives where the turbulence structure (which drives the secondary motion for these inertia-dominated flows) may be only marginally different from that for a Newtonian fluid flow. There are, in addition, doubts about the validity of some of the very early data (e.g. [11] for which the u' values are roughly a factor of 2 higher than most comparable data). Ducts with aspect ratios in the range 10–19 are more typical [16–24] but in many cases the turbulence data are limited to the streamwise (or axial) component of velocity u'[1] [16], or the axial and normal v' components of velocity together with the Reynolds shear stress $-\rho\overline{uv}$ [17–23] but not the third com-

[1] In this paper u' represents the root-mean-square value of the fluctuating component of the streamwise (or axial) velocity component; v' is the rms value of the normal component of the fluctuating velocity and w' is the rms value of the lateral component.

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Table 1
Summary of previous data (symbols correspond to data shown in Fig. 8).

Ref	Author(s)	Year	AR	Fluid(s)	Data	(Sets)
[10]	Logan	1972	1	50 ppm polyox	u', v', $\overline{uv}$	(2)
[11]	Rudd	1972	1	100 ppm PAA Separan AP30	u', v'	(1)
[16]	Reischman and Tiederman (☆)	1975	10.7	100 ppm PAA Separan AP273, 100 ppm Magnifloc 837A, 100 ppm Polyox WSR-301	u'	(3)
[24]	Gampert and Delgado (□)	1985	19	50 and 100 ppm PAA Praestol PR2850	u', v', w', $\overline{uv}$	(2)
[18]	Willmarth, Wei and Lee (△)	1987	12	10 ppm Polyox	u', v', $\overline{uv}$	(2)
[12]	Gampert and Yong	1988	1	50 and 100 ppm PAA Praestol 2360	u', v', $\overline{uv}$	(4)
[17]	Luchik and Tiederman (⊗)	1988	10	1.3 and 2.1 ppm PAA Separan AP273	u', v', $\overline{uv}$	(2)
[13]	Gampert and Yong (×)	1990	1	50 and 100 ppm PAA Praestol 2360	u', $\overline{uv}$	(4)
[19]	Harder and Tiederman (▽)	1991	10	3–5 ppm PAA Separan AP273	u', v', $\overline{uv}$	(2)
[20]	Wei and Wilmarth (▷)		11.9	10 ppm Polyox WSR-301	u', v', $\overline{uv}$	(3)
[21]	Gampert and Rensch (◁)	1996	1& 19	19 5–150 ppm PAA Praestol 2360	u', v', $\overline{uv}$	(23)
[22]	Warholic, Massah and Hanratty (+)	1999	12	0.25–50 ppm PAA Percol 727	u', v', $\overline{uv}$	(8)
[14]	Escudier and Smith (◊)	2001	1	0.1% CMC/0.1% XG, 0.125% PAA Separan AP273	u', v', w', $\overline{uv}$	(2)
[23]	Warholic, Heist, Katcher and Hanratty (○)	2001	12	1.24 and 50 ppm PAA Percol 727	u', v', $\overline{uv}$	(2)
[15]	Gampert, Braemar, Eich and Dietmann (♣)	2004	1	100 ppm–0.015% PAA Praestol 2300, 50–400 ppm XG	u', v', $\overline{uv}$	(8)

ponent of velocity w'. In fact, we have identified only one previous study [24] which also includes measurements of w': as will be discussed later, all three components of velocity are required, together with the Reynolds shear stress, if the turbulence anisotropy is to be quantified. With one exception [23], in which particle-image velocimetry was used, all previous measurements were made using laser Doppler anemometry. A further limitation of previous work is to relatively low polymer concentrations where the liquid viscosity is essentially that of the solvent (invariably water). Even where the concentration has been sufficiently high to significantly change the liquid rheology, little information is given about the viscosity-shear rate curve. In only two cases, [15] and [22], are flow curves provided to quantify the degree of shear thinning though in the former paper the viscosity data for high shear rates were affected by Taylor instabilities and in both cases the ratio of maximum to minimum shear viscosity was less than 20. Finally, in many instances the data provided are very limited (e.g. a single set of profiles), incomplete (e.g. no information about wall shear stress or bulk velocity) or of questionable accuracy (e.g. measured values of friction factor for a Newtonian fluid significantly different from values calculated from well-established correlations [26]).

2. Experimental arrangement and instrumentation

Although new, the flowloop used here is similar in design to facilities used in previous research at the University of Liverpool [7,14,25]. The new loop incorporates a rectangular duct comprising six 1.2m long stainless-steel modules with an internal cross-section of height H = 25 mm and width $w = 298$ mm (hydraulic diameter $D_H = 2wH/(w+H) = 46$ mm, aspect ratio $w/h = 11.92$). Five of the modules are upstream of the Perspex, stainless-steel and glass test section, length 250 mm, which is therefore located 6 m (240H) from the duct inlet. Flow is provided by a progressive cavity pump, Mono type E101, with a maximum flowrate of 0.025 m^3/s. The flow rate was measured by an Endress and Hauser Promag P electromagnetic flowmeter. The flow enters and leaves the rectangular duct through transition sections which change gradually in cross-section from circular to rectangular and vice versa.

In the test section, shown schematically in Fig. 1, a unique open-slot arrangement, inspired by the open-channel work of Poggi et al (2002) [27], allows essentially unimpeded access of the LDA laser beams to the flowing liquid. This technique permits simultaneous and coincident measurement of the mean axial velocity u, the RMS value of the fluctuating axial velocity component u' and the RMS fluctuating velocity component normal to the duct surface v', and hence the determination of the Reynolds shear stress $-\rho\overline{uv}$, without the need for a complex optical arrangement such as has been used in the past (e.g. [18–20],). The third fluctuating velocity component w', orthogonal to u' and v', was measured separately. The streamwise velocity was remeasured simultaneously with the w' data to provide both a consistency check and a way of monitoring polymer degradation. A Dantec FibreFlow 2D LDA system, comprising a 60 × 10 probe and 55X12 beam expander together with Dantec BSA 57N20 and 57N10 burst spectrum analyser signal processors was used to measure the distributions of the mean and fluctuating velocities. The optical system produces a measuring volume with length 180 μm and diameter 20 μm. The streamwise pressure gradient was estimated from measurements of the pressure difference between pressure tappings installed in the stainless-steel modules (i.e. with 1.2 m separation) using a Validyne DP15-30 pressure transducer linked to a Validyne CD223 digital indicator. The pressure transducer was calibrated periodically against an MKS Baratron differential pressure transducer (1000 torr fsd). Fluid temperature was monitored using a platinum-resistance thermometer installed at the downstream end of the duct.

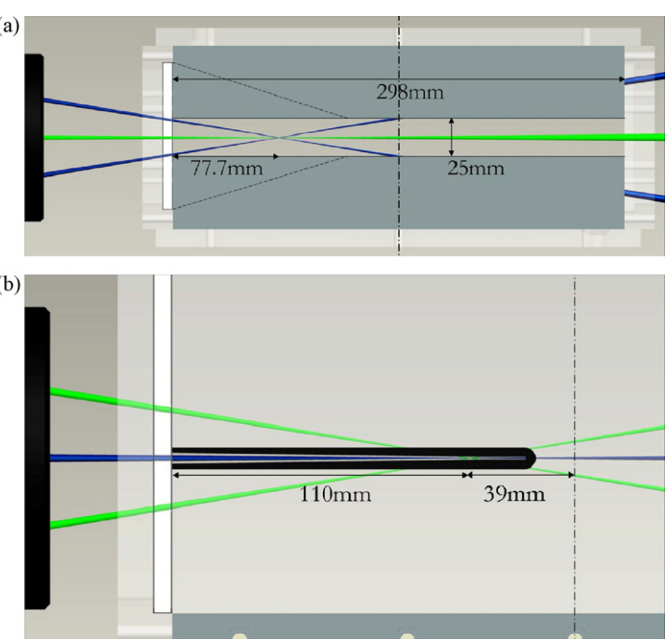
(a)
(b)


Fig. 1. Schematic of the test section showing the LDA access slit: (a) cross-section, (b) plan view.